*Proceedings of the 2nd International Conference*
*The Institution of Engineers, Bangladesh*
*Electrical Engineering Division*
*23-24 Oct, 2002*

# Application of Superconducting Magnetic Energy Storage Unit as Continuous VAR Controller

**M.R.I. Sheikh*, M.G. Rabbani#, and M.M. Ali$**
Department of Electrical and Electronic Engineering
Bangladesh Institute of Technology, Rajshahi, Rajshahi – 6204, Bangladesh
**Email : ris@librabd.net**
*Assistant Professor # Associate Professor $ Professor

## Abstract:

The 12-pulse converter bridge associated with a superconducting magnetic energy storage (SMES) unit has a certain freedom in choosing the reactive power consumption. Utilizing this Q-modulation capability of the converter, SMES unit can act as a continuous VAR controller while acting as a load frequency stabilizer at the same time. In this paper, a comprehensive control strategy to achieve the reactive power modulation has been formulated and applied in the test network. Under four-quadrant operation of the converter , SMES unit supplies leading Var when the system voltage go down and also supplies lagging Var when the system voltage increases in the load. It is found that the proposed mode of control greatly improves the overall performance of the Q-V loops as well as the P-f loops of a power system.
**Keywords:** Energy Storage, Superconducting Magnet, Reactive power control.

## 1. Introduction

Power system oscillations occur when there are system disturbances such as sudden small load perturbations or faults, which continuously disturb the normal operation of a power system. The damping of the system must be such that the synchronous generators can return to their steady state conditions after the disturbances [1]. Especially when the load-end of the transmission line experiences sudden load perturbations, the generators need continuous control to suppress undesirable oscillations in the system. Many countermeasures have been suggested by researchers to increase the damping. These include power system stabilizers [2-3], optimal control of the turbine-governor system [4], and the use of static phase shifters [5].

In power systems, continuous reactive power compensation in the load end of transmission lines is generally required for static and dynamic voltage control and system stability preservation. In substations where the nature of load requires high speed of response, a continuous reactive power adjustment ability, the static VAR systems (SVS), only of fixed capacitor, thyristor-controlled-reactor (FC-TCR) type have been used as a viable and desirable option.

When operating in the continuous current mode, the 12-pulse bridge converter of the SMES unit [6] creates a phase difference between the input voltage and fundamental component of current waveform and hence always draws lagging VAR. To achieve a complete VAR control, covering the leading and lagging VAR regions, the SMES unit is suitable for 4-quadrant operation [7]. The purpose of the present paper is to show that with proper control, the SMES unit plays a vital role of a continuous VAR compensator, while acting as a load frequency stabilizer at the same time. Thus SMES units, if located in load-end substations, would obviate the use of any additional SVS. The schematic diagram of the proposed scheme is given in Fig. 1.

Since SMES unit can be operated in full $0^0$-$360^0$ firing angle ranges, like active power, the Q-consumption can also be both positive and negative. Under four-quadrant mode, the following combinations can be achieved;

(i) P positive and Q positive → Rectifier mode, SMES unit supplies lagging Var.
(ii) P negative and Q positive → Inverter mode, SMES unit supplies lagging Var.
(iii) P negative and Q negative → Inverter mode, SMES unit supplies leading Var.
(iv) P positive and Q negative → Rectifier mode, SMES unit supplies leading Var.

## 2. Earlier Work on VAR Control Using SMES Unit

The Bonneville power administration (BPA) of USA has installed an SMES unit to damp the low frequency oscillations in the Pacific AC intertie [7]. In this unit, the active power is controlled by the narrow-band noise signal of the intertie current and attempts have been made to control the reactive power in such a way that it has least effect on the power system. For this reason, the buck-boost mode of control has been

investigated and the result of the commissioning tests has been reported in [7]. This work considers three major operating modes, namely, the constant P mode, the constant Q mode, and the minimum Q mode. However, it does not consider the reactive power modulation of such units to perform any dynamic duties.
In [8], a novel scheme of static VAR compensation, called SAVAR (Superconductor application for VAR control) was presented. The work aims at reducing the losses in a conventional SVS utilizing the fact that a superconducting coil has virtually no losses for dc current. The SAVAR concept proposes the use of a superconducting coil in which a nominally constant direct current is maintained, and to which the appropriate phases of the ac supply are periodically connected. However, it was later estimated that the economic advantage of a SAVAR unit compared to a conventional SVS is marginal, and accordingly the program was terminated in 1981.
The scheme proposed in the present paper makes effective use of the SMES unit for reactive power modulation as well as active power modulation and hence its economic advantage is expected to be stronger than that of the earlier schemes.

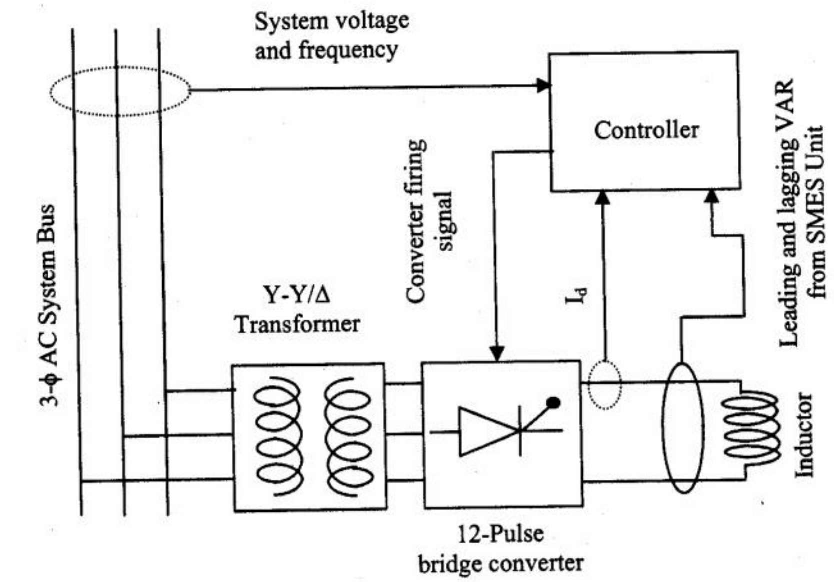


**Fig. 1.** The schematic diagram of the proposed scheme

## 3. VAr Modulation Capability of the Converter

In the present mode of control the VAr modulation range of the converter, at any instant of time, is constrained by the active power transfer and the current through the inductor. According to the theory of converter operation [5], the voltage $E_{di}$ in the dc side in presence of the source inductance, due to each constituent 6-pulse converter is given by,

$$E_{di} = V_{d0} \cos\alpha_i - R_c I_d \tag{1}$$

Where, $V_{d0}$: Ideal no-load maximum direct voltage of the 6-pulse bridges

$\alpha$ : Converter firing angle

$I_d$ : Inductor current, and

$R_c$: Equivalent commutating resistance due to the source inductance [5].

The subscript 'i' identifies the 6-pulse converter number 1 or 2.

Then

$$P_{di} = V_{d0}.I_d.\cos\alpha_i - Id^2.Rc \tag{2}$$

Where, $P_{di}$ is the active power transfer through bridge i. This gives the equation for the input power factor as

$$\cos\phi_i = \cos\alpha_i - I_d.R_c/V_{d0} \tag{3}$$

The active and reactive power loads presented by the 12-pulse converter under equal $\propto$-mode are expressed as

$$P_d = 2V_{d0}\, I_d \cos\alpha \tag{4}$$

$$Q_d = 2V_{d0}\, I_d \sin\alpha \tag{5}$$

## 4. The P-Q Control Strategy for on-Line Operation of SMES unit

The proposed controller of the SMES unit performs its task by receiving the measured values of area control error ($\Delta f$), bus voltage deviation ($\Delta V_L$), inductor current deviation ($\Delta I_d$), VAR setting of the SMES unit without using the capacitor bank.

At any time the reactive power modulation range is calculated from the values of $P_d$ and $I_d$. A reactive power demand signal is generated from the bus voltage deviation $\Delta V_L$ following the equation:

$$Q_{demand} = K_V . \Delta V_L \tag{6}$$

where, $K_V$ is the gain corresponding to the voltage deviation. The actual reactive power consumption of the converter is varied continuously depending on the $Q_{demand}$ signal while keeping within the Q-modulation range. When the required Q setting reaches the limits, the adequate switching signal is sent to the SMES unit so that the required reactive power setting of the converter remains within the available range.

## 5. Effect of the Proposed P-Q Control

In this section, the effects of the proposed P-Q control (as shown in Fig.2) method have been demonstrated with the help of a simple single area power system. The purpose is to show the behaviour of the SMES unit under the control scheme. The magnitude of its impact on the power system would depend on the type of power system and the nature of the load.

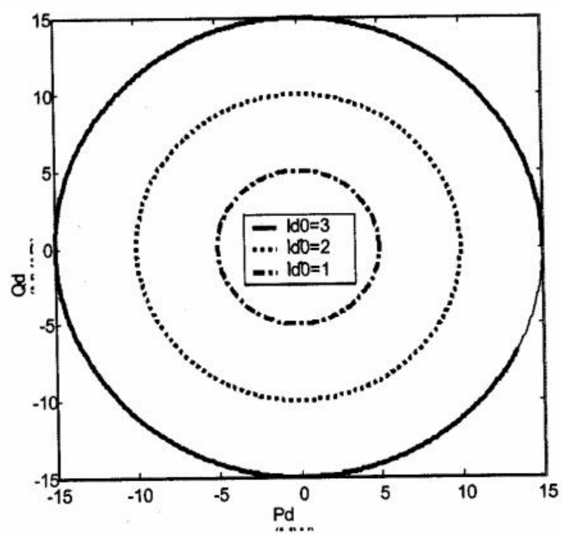


**Fig.2:** Effect of $I_d$ on P-Q locus of 12-pulse converter under equal-$\propto$ mode of control

The study of the effects of simultaneous modulation of reactive as well as active power on power system dynamic performance requires a power system model coupling the reactive power-voltage and active power-frequency loops. Moreover, the effect of Q-modulation is appreciable only when the SMES unit is placed at the load end of a transmission line [9], sufficiently distant from the generator bus. For this reason, the single area power system shown by the single line diagram in Fig. 3 is chosen for study. The purpose is to highlight the behaviour of the SMES unit and its economical advantage in the proposed mode of control.

## 6. System Modeling

The following assumptions are made in the system modeling [10]:

1. The reheat turbine type thermal plant supplies to a single generator whose capacity is 2000MW.
2. The generator is equipped with automatic voltage regulator (AVR) with stabilizing speed feedback.
3. The generator is cylindrical rotor type and the resistances of the generator and the line are negligible in comparison with the reactances.
4. Strong coupling is present between P-f and Q-V loops. The coupling effect can be shown as follows.

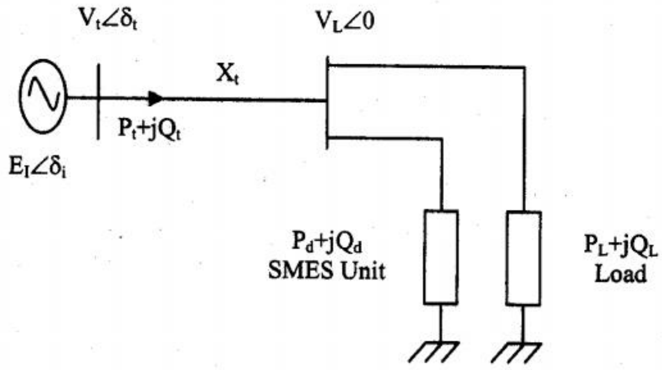


**Fig. 3**: Single line diagram for test network.

In general, the active and reactive powers taken by the load are functions of frequency and voltage. Hence,

$$\Delta P \approx \left(\frac{\partial P}{\partial f}\right)\Delta f + \left(\frac{\partial P}{\partial|V|}\right)\Delta|V| \tag{7}$$

$$\Delta Q \approx \left(\frac{\partial Q}{\partial f}\right)\Delta f + \left(\frac{\partial Q}{\partial|V|}\right)\Delta|V| \tag{8}$$

where, $\Delta P$ and $\Delta Q$ are the changes in the real and reactive loads as caused by relatively small variations $\Delta f$ and $\Delta|V|$ in frequency and voltage.

Let the step load change causing the disturbance be ($\Delta P_L + \Delta Q_L$). The consequent changes in frequency and voltage, $\Delta f$ and $\Delta V_L$, would in turn affect the loading. Therefore, the net change in real and reactive loading $\Delta P_{LN}$ and $Q_{LN}$ can be expressed as

$$\Delta P_{LN} \approx \Delta P_L + \left(\frac{\partial P_L}{\partial f}\right)\Delta f + \left(\frac{\partial P_L}{\partial|V_L|}\right)\Delta|V_L| \tag{9}$$

$$\Delta Q_{LN} \approx \Delta Q_L + \left(\frac{\partial Q_L}{\partial f}\right)\Delta f + \left(\frac{\partial Q_L}{\partial|V_L|}\right)\Delta|V_L| \tag{10}$$

$\frac{\partial Q_L}{\partial f}$ is neglected because of its less practical importance [11].

The net incremental power $\Delta P_t$ out of the synchronous machine is given by the sum of $\Delta P_G$ (the incremental generator power due to governor action) and $-\frac{2H}{f^0}\frac{d}{dt}\Delta f$ (the power derived out of the inertia of the rotor through speed change). Hence

$$\Delta P_t = \Delta P_G - \frac{2H}{f^0}\frac{d}{dt}\Delta f \tag{11}$$

With the addition of SMES unit at the load end, the active and reactive powers balance at the generator bus can be expressed as

$$\Delta P_t = \Delta P_{LN} + \Delta P_d \tag{12}$$

$$\Delta Q_t = -\Delta Q_{LN} + \Delta Q_d + \Delta Q_t \tag{13}$$

where $\Delta Q_t$ is the change of reactive power loss in the transmission line.

Using equations (9), (11) and (12), the following is obtained:

$$\Delta P_G - \frac{2H}{f^0}\frac{d}{dt}\Delta f = \Delta P_L + \left(\frac{\partial P_L}{\partial f}\right)\Delta f + \left(\frac{\partial P_L}{\partial|V_L|}\right)\Delta|V_L| + \Delta P_d$$

$$\frac{d}{dt}\Delta f = \frac{f^0}{2H}\left[\Delta P_G - \Delta P_L - \frac{\partial P_L}{\partial f}\Delta f - \left(\frac{\partial P_L}{\partial|V_L|}\right)\Delta|V_L| - \Delta P_d\right] \tag{14}$$

## 7. Simulation Results

Non-linear dynamic equations are used in the solution process. They are solved using 4th order R-K method. Two case studies were conducted on the system: case 1 corresponding to sudden load change of (0.005+j0.005) p.u. and case 2 corresponding to (0.008+j0.008) p.u.

The frequency and load voltage deviations of the power system without SMES unit for the above cases are shown in Fig. 4 and 5 respectively. In case 1, the maximum frequency and the starting load voltage deviations are 0.0183 Hz and 0.0032 p.u. respectively. Also, the maximum frequency and the starting load voltage deviations in the case 2 are 0.028 Hz and 0.0048 p.u. respectively. The performance of the AVR shows that it is fast enough to pull back the voltage following a sudden application of load as shown in Fig. 4 and 5. The coupling effect between the Q-V and P-f loops is the main cause for the oscillations.

The response of the power system with the SMES unit under the same disturbances for the cases mentioned above are also shown in Fig. 4 and 5. It is evident that due to the addition of the SMES unit, there is a significant improvement in dynamic performance of the power system.

In both these cases, Q-modulation along with the reactive power provided by SMES unit improves the load voltage profiles while the P-modulation by the SMES unit reduces the oscillation in the frequency.

## 8. Conclusions

This paper presents a new mode of controlling the SMES unit for improving the transient performance of single area power system. A simple integral controller was used to design frequency and voltage controllers to generate required control signals for 12-pulse converter from active and reactive power modulation using both frequency and voltage error signals, makes the proposed mode of control is cost effective and more sensitive. As a result, P-Q modulation is effectively used. Four-quadrant operation makes it possible to handle different type of load changes. Under smaller disturbances, proposed controller provides a little gain in system frequency damping and inductor current variations. However, when the degree of disturbance increases, proposed controller shows its clear superiority in every aspect.

In the proposed mode of control it is observed that the time taken to damp the system oscillations is very small. Also this occurs with a small deviation of the inductor current. It is suggested that with the proposed mode of control, the use of switching capacitor banks can be ignored, so system is cost effective. The control circuit required is very simple and easy to implement.

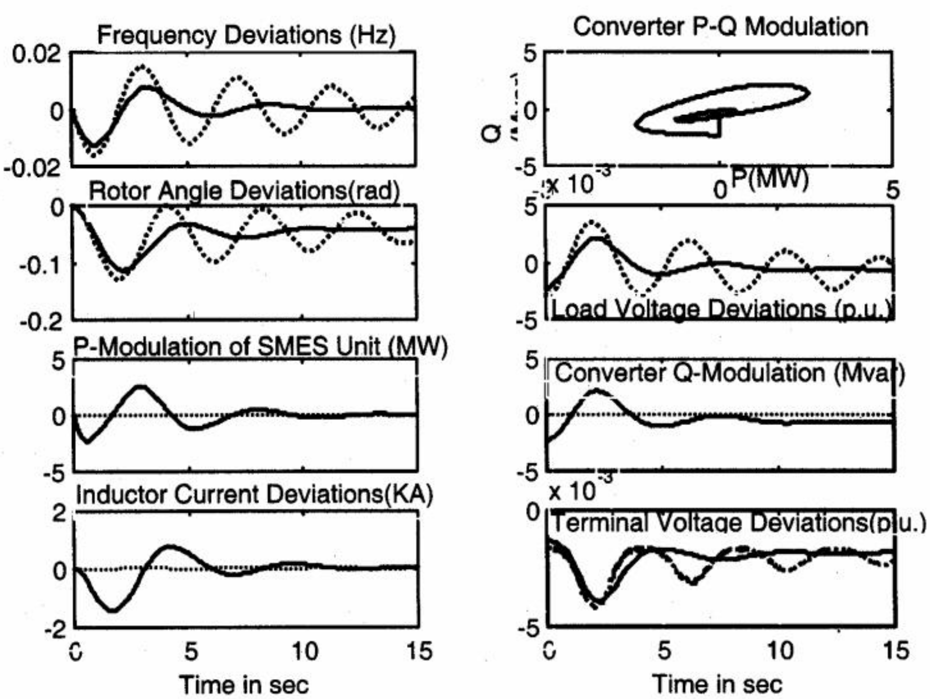


**Fig. 4.** Response of the power system after addition of SMES unit [**Case 1**]

—— with SMES unit and ...... without SMES unit

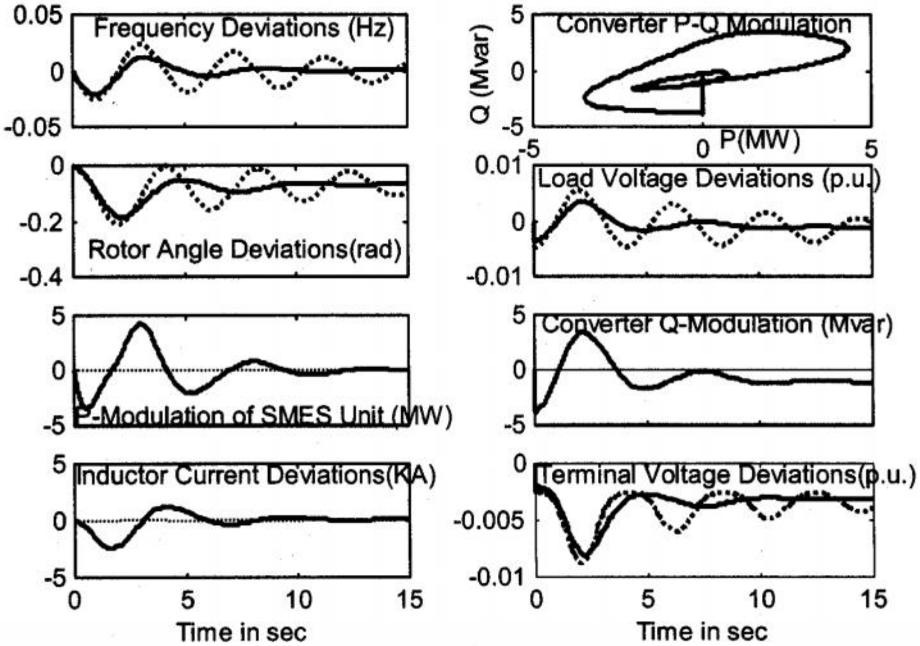


**Fig. 5.** Response of the power system after addition of SMES unit [**Case 2**]

—— with SMES unit and ..... without SMES unit

## References:


[1] P.M. Anderson and A.A. Fouad, Power System Control and Stability, Lowa State University Press, Ames, lowa, 1977.

[2] E.V. Larsen and D. A. Swann, Applying power system stabilizers, IEEE Trans. Power Appar. and Syst., PAS-100 (1981), 3017-3046.

[3] O. P. Malik, G.S. Hope, S. J. Cheng, and G. Hancock, A multi - microcomputer based dual-rate self-tuning stabilizer, Paper 86JPGC 652-2, IEEE/PES Joint Power Generation Conf. , Portland, OR, USA 1986. Paper 86JPGC 652-2.

[4] S. C.Tripathy, T. S. Bhatti, and C. S.Tha, et. al., Sampled data automatic generation control analysis with reheats steam turbines and governor dead - band effect, IEEE Trans. on Power Appar. Syst., PAS-13 (1984), 1045-1051.

[5] H. Stemmeler and G. Guth, The thyristor controlled static phase-shifter a new tool for power flow control in ac power system, Brown Boveri Review-69 (1982), 73-78.

[6] S. Banerjee, S. C. Tripathy and J. K. Chatterjee, Application of magnetic energy storage unit as load- frequency stabilizer, a companion paper, submitted for presentation at the IEEE, PES summer meeting, 1989.

[7] H. J. Boening and J. F. Hauer, Commissioning test of the bonneville 30 MJ super-conductive magnetic energy storage unit, IEEE Trans. on Power Appar. Syst.,vol. PAS - 104 ,no. 2 February 1985, pp. 302-312.

[8] H.J. Boenig, F. Cibulka, 'A Static VAR Compensator Using a Superconducting Coil', IEEE Transactions on power apparatus and system, PAS-101, No. 10, October 1982, pp. 3988-3995.

[9] S. Banerjee, J. K. Chatterjee, and S. C. Tripathy, Application of magnetic energy storage unit as continuous VAr controller, IEEE Trans. on Energy Conversion,5 (1990) 39-45.

[10] E. W. Kimbark, Direct Current Transmission, A book, New York, John Wiley and Sons Inc. , NY, 1971.

[11] O. I. Elgerd, Electric Energy systems Theory, McGraw-Hill Inc., NY, 1971.

[12] S. Banerjee, J. K. Chatterjee, and S. C. Tripathy, Application of magnetic energy storage unit as load frequency stabilizer, IEEE Trans. on Energy Conversion, 5 (1990) 46-51.

[13] Y. Mitani , K. Tsuji, and Y. Murakami , Application of superconducting magnetic energy storage to improve power system dynamic performance, IEEE Trans. Power Syst., 3(1988), 1418-1425.